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Cloud Modeling

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1. Introduction

Numerical cloud models have been developed and applied extensively to study cloud-scale and mesoscale processes during the past four decades. The distinctive aspect of these cloud models is their ability to treat explicitly (or resolve) cloud-scale dynamics. This requires the cloud models to be formulated from the non-hydrostatic equations of motion that explicitly include the vertical acceleration terms since the vertical and horizontal scales of convection are similar. Such models are also necessary in order to allow gravity waves, such as those triggered by clouds, to be resolved explicitly. In contrast, the hydrostatic approximation,

usually applied in global or regional models, does not allow the presence of gravity waves.

The earliest form of cloud model is the one-dimensional entraining bubble or plume model. The one-dimensional cloud model can treat the lateral entrainment of environmental air as the buoyant cloud rises through the cloud environment. This type of cloud model was used extensively to study the cloud seeding problem. In the 60's, a two-dimensional anelastic cloud model that filtered out sound waves was developed to study cloud development under the influence of the surrounding environment. In the 70's, three-dimensional cloud models were developed. The effect of model designs (i.e., slab vs axis-symmetric, wind shear effect) on cloud development and liquid water content were the major foci in 70's. Also, the dynamics of midlatitude supercells, that are usually associated with tornados, was another major focus in the 70's. In the late 70's and early 80's, another type of cloud model, the cumulus ensemble model, was developed to study the collective feedback of clouds on the large-scale tropical environment with the aim of improving cumulus parameterization in large-scale models. The effect of ice processes on cloud formation and development, stratiform rain processes and their relation to convective cells, and the effect of wind shear on squall line development were the other major areas of interest for cloud resolving models in the 1980's. The impact of radiative processes on cloud development was also investigated in the late 80's. In the 1990's, cloud resolving models were used to study multi-scale interactions, cloud chemistry interaction, idealized climate variations, and surface processes. The cloud models were also used for the development and improvement of satellite rainfall retrieval algorithms. The major advantages of using cloud resolving models are their ability to quantify the effects of each physical process upon convective events by means of sensitivity tests (eliminating a specific process such as evaporative cooling, ice processes and terrain), and their detailed dynamic and thermodynamic budget calculations. Table 1 lists the major highlights that used the cloud resolving model over the past four decades.

During the past 25 years, observational data on atmospheric convection has been accumulated from measurements by various means, including radars, instrumented aircraft, satellites, and rawinsondes in special field observations. This has made it possible for cloud resolving modelers to test their simulations

against observations, and thereby improve their models. In turn, the cloud models have helped scientists to understand the complex dynamical and physical processes that interact in atmospheric convective systems, and for which observations alone still cannot provide a complete and consistent picture. Over the last 25 years, the cloud models have become increasingly sophisticated through the introduction of improved microphysical processes, radiation and boundary-layer effects, and improved turbulent parameterizations for subgrid-scale processes. In addition, the availability of exponentially increasing computer capabilities has resulted in time integrations increasing from hours to days, domain grids boxes (points) increasing from less than 2000 to more than 2,500,000 grid points with 500 to 1000 m resolution, and 3-D models becoming increasingly prevalent. The cloud resolving model is now at a stage where it can provide reasonably accurate statistical information of the sub-grid, cloud-resolving processes poorly parameterized in climate models and numerical prediction models.

2. Major Characteristics of Cloud (Resolving) Models

The equations which govern cloud scale motion in the cloud resolving model are either anelastic or fully compressible. For the anelastic system, sound waves are filtering out by neglecting the local variation of air density with time in the mass equation. For strictly numerical reasons it is sometimes convenient to use fully compressible equations. Novel characteristics of the cloud model are explicit microphysical processes (involving the phase changes of water and precipitation), atmospheric turbulence (dissipation of mean flow kinetic energy), turbulent processes at oceanic or terrestrial boundaries (latent and sensible heat fluxes into the atmosphere), and radiative transfer processes (complex processes in the presence of clouds).

(a) Microphysics and Precipitation

Figure 1 shows the schematic of a two-class liquid (cloud water and rain droplet) and three-class ice (cloud ice, snow and graupel/hail) microphysics scheme that is widely used in modern cloud models. The shapes of liquid and ice are assumed to be spherical. The warm cloud microphysics assumes the population of water particles is bimodal, consisting of small cloud water droplets whose

terminal velocity is minute compared to typical vertical air velocities, and large rain droplets that obey certain size distributions based on limited observations. Condensation, evaporation, and autoconversion/collection processes (from small cloud droplets to large rain droplets) are parameterized. The ice microphysics assumes three types of particles: small cloud ice whose terminal velocity is also minute compared to typical vertical air velocities, snow whose terminal velocity is about $1\text{--}3\text{ m s}^{-1}$, and large size graupel or hail with faster terminal velocities. Graupel has a low density and a high intercept (i.e., high number concentration). In contrast, hail has a high density and a small intercept. The choice of graupel or hail depends on where the clouds or cloud systems developed. For tropical clouds, graupel is more representative than hail. For midlatitude clouds, hail is more representative. More than 25 transfer processes between water vapor, liquid and ice particles are included. They are the growth of ice crystals by riming, the aggregation of ice crystals, the formation of graupel and hail, the growth of graupel and hail by the collection of supercooled rain drops, the shedding of water drops from hail, the rapid growth of ice crystals in the presence of supercooled water, the melting of all forms of ice, deposition and the sublimation of ice. Only large rain droplets, snow and graupel/hail fall towards the ground as precipitation.

Only recently have some cloud resolving models adopted a two-moment four-class ice scheme which combines the main features of the three-class ice schemes by calculating the mixing ratios of both graupel and frozen drops/hail. Additional model variables include the number concentrations of all ice particles (small ice crystals, snow, graupel and frozen drops), as well as the mixing ratios of liquid water on each of the precipitation ice species during wet growth and melting for purposes of accurate active and passive radiometric calculations.

(b) Turbulence

In cloud models, the larger eddies are explicitly calculated. Those much smaller than the grid resolution have to be parameterized. There is an implicit assumption that small scales approximate to an inertial sub-range where the energy spectrum is in statistical equilibrium and there is an energy cascade from the resolved scales to the dissipation scales. The most sophisticated turbulence parameterization used in cloud models is a third-moment closure. Typical cloud

models used simple k -type (first-order) turbulence closure or determine the coefficient k from the turbulence kinetic energy (TKE) equation (one-and-a-half order) either diagnostically or prognostically. In the prognostic TKE method, thermodynamic stability, deformation, shear stability, diffusion, dissipation and transport of subgrid energy are included. In the diagnostic method, deformation and stability are used for computing the k coefficient.

(c) *Radiation*

The direct calculation of radiative transfer is very expensive, especially where multi-phase water substance is concerned. In general, emission and absorption by water vapor and cloud droplets are considered using two-stream longwave radiation methods in cloud models. Broadband methods for longwave radiation combine the effects of reflection, emission, and transmission by cloud droplets and air molecules. The treatment of shortwave radiation in cloud models is also based on broadband approximations. One major issue is how to parameterize cloud optical properties (optical thickness), especially in the presence of the ice phase, considering the important impact of radiative heating and cooling profiles within clouds. Noted that only limited observations are available upon which to base parameterization methods for ice clouds.

The use of a fully explicit microphysics scheme (liquid and ice) and a fine horizontal resolution can provide relatively realistic cloud optical properties, which are crucial for determining the radiation budgets. With high spatial resolution, each atmospheric layer is considered either completely cloudy (overcast) or clear. No partial cloudiness is assumed.

(d) *Ocean Surface fluxes*

Two types of ocean surface schemes are used in the cloud models. The first is a simple bulk aerodynamic formula. The transfer coefficients for momentum, sensible heat, and latent heat fluxes are only a function of wind. The second type of surface scheme is more complex but is still primarily based on the bulk scheme. The transfer coefficients for momentum, sensible heat, and latent heat fluxes are based on the Monin-Obukhov similarity theory of the atmospheric surface layer. The parameters, such as the roughness lengths, are closely related

to the sea surface characteristics and the turbulence characteristics. In very low wind speed conditions, the similarity profile becomes singular. This singularity was effectively eliminated by adding a convective velocity so that the ocean surface fluxes would not be zero under windless conditions. The exchange coefficients in the simple bulk aerodynamic formula method and in the second bulk flux algorithm are different in two ways. First, in the lower wind speed region (less than 4 m s^{-1}), the exchange coefficients in the complex bulk scheme increase with decreasing wind speed in order to account for the convective exchange at low wind speeds. Secondly, the coefficients in the simple bulk aerodynamic formula linearly increase with respect to the wind speed, while the complex bulk scheme go down with wind speed when wind speed is greater than 5 m s^{-1} . These differences in the exchange coefficients can effect the rainfall amounts and boundary structures.

(e) *Land Surface Processes*

Recently, a detailed interactive land surface process model of the heterogeneous land surface (soil and vegetation) and adjacent near-surface atmosphere has been used in the cloud model to study the impact of soil moisture patches and atmospheric boundary conditions on cloud structure, rainfall, and soil moisture distribution. The land surface model basically consists of three elements. These are: (1) a soil module that includes at least seven water reservoirs (i.e. plant internal storage, dew/intercepted precipitation, surface material (no roots), a topsoil root layer, a subsoil root layer, and two deeper layers that regulate seasonal and interannual variability of the soil hydrology, (2) a surface slab of vegetation, litter and other loose material which shades the soil and acts as the source for sensible heat flux, and which intercepts precipitation and dew, and (3) the surface layer of the atmosphere (up to the lowest computational level of the model to which it is coupled) within which the fluxes of sensible heat and water vapor are calculated.

(f) *Use of cloud models*

The use of cloud models to study convective processes can generally be categorized into two groups. The first approach is so-called "cloud ensemble modeling". In this approach, many clouds of different sizes in various stages of

their lifecycles can be present at any model simulation time. The large-scale effects (forcing) are always applied to the model continuously. These are derived from observations such as convergence in the wind field. Cyclic lateral boundary conditions (to avoid the reflection of gravity waves) and a large horizontal domain (to allow for the existence of an ensemble of clouds) are required. The clouds simulated from this approach could be termed "*continuously forced convection*". On the other hand, the second type of cloud modeling does not require large-scale effects to initialize and maintain cloud development. This type of simulation requires initial temperature and water vapor profiles which have a medium to large convective available potential energy (CAPE), and an open lateral boundary condition is always used. The modeled clouds are then initialized with either a cool pool, warm bubble or surface processes (i.e., land/ocean fluxes). These modeled clouds could be termed "*self-forced convection*"; they are mainly for case study (i.e., 6-12 h of time integration).

Most attention is devoted to precipitating cloud systems which are amenable to the cloud resolving model approach because their primary properties can be resolved with grid lengths of about 1 km. This means that a modern cloud model's horizontal domain is on the order of 1000s of km in a two-dimensional framework and 100s of km on a side in a three-dimensional framework. The cumulus ensemble modeling or "*continuously forced convection*" approach is also used to understand and quantify precipitation processes associated with precipitating systems that originate in different geographic locations [e.g., the west Pacific warm pool region (TOGA COARE) and the eastern Atlantic region (GATE)].

3. Modeling Tropical Convective Systems - Thermodynamic Aspects

(a) Rainfall Pattern and Cloud Structures

Figures 2 (a) and (b) show the temporal variation of the cloud model simulated domain mean surface rain rate for the west Pacific warm pool region and eastern Atlantic region, respectively. There are more convective systems simulated by the cloud model in the west Pacific warm pool region than in the eastern Atlantic region. This is due to the stronger large-scale forcing imposed in the west Pacific warm pool region simulation. The model-simulated surface

precipitation pattern showed a very complex structure for the west Pacific warm pool region compared to the eastern Atlantic region. Overall, the model-simulated west Pacific warm pool region cloud systems propagated in one direction while the individual cells embedded within the systems propagated in the opposite direction. In addition, the cloud tops propagate in the opposite direction of the associated surface precipitation. These two hierarchies of convective organization are in good agreement with satellite observations. In the eastern Atlantic region simulation, only shallow convective systems developed during the first day. Then, deep convective clouds and non-squall (slow moving) cloud systems developed and propagated westward with the mean wind. Squall line type (fast moving) cloud systems developed after September 4. After September 6, the systems simulated by the cloud model were less organized and produced less surface precipitation compared to the non-squall and squall systems.

The cloud-resolving-model-simulated domain-averaged surface rainfall (mm), and stratiform amount (percentage) for both the west Pacific warm pool region and the east Atlantic region are shown in Table 2. The ratios between evaporation and condensation, sublimation and deposition, and deposition and condensation were examined for both cases. These ratios illustrate the relative importance of warm versus ice processes and source and sink terms associated with water vapor over the course of the west Pacific warm pool region and east Atlantic region simulations. The microphysical processes are broken down according to convective organization (i.e., slow-moving, fast-moving, less organized convective episodes from the east Atlantic region, vigorous deep convection and weaker convective events during the Westerly Wind Burst period). More surface rainfall was simulated in the model for the west Pacific warm pool region than for the east Atlantic region. Also, a higher stratiform component was simulated for the west Pacific warm pool region. The dominance of warm rain processes in the east Atlantic region squall and non-squall convective systems may explain the smaller stratiform rain amounts simulated by the model. Very little ice processes on September 6 and 8 are an indication of shallow convection. In contrast, ice processes are quite important for both active and relatively inactive convective periods over the west Pacific warm pool region. Weak convective episodes in both the east Atlantic and west

Pacific warm pool regions had high evaporation to condensation ratios compared to more intense convective periods.

Figure 3 shows one example of the three-dimensional cloud-model-simulated cloud systems in the west Pacific warm pool region. Many clouds/cloud systems at different stages of their life cycles are present. Both the cloud-scale and mesoscale are simulated. Organized mesoscale convective systems consist of a linear group of cumulonimbi (convective) usually along the leading edge of the system in the direction of propagation and, in the mature stage, an associated anvil containing a broad area of light precipitation (stratiform). Stronger upward air motion is closely associated with the convective cells located at the leading edge of the precipitating systems. These convective cells tilt with height mainly along the mean wind shear. Downward air motion is located behind the leading edge of the system and develops mainly at low levels where evaporative cooling is the dominant microphysical process. The effects of cold pool forcing on new convective cell growth are important. There is upward motion above the downward region. Typically, the level that separates the upward and downward region is the 0 °C level. Gravity waves (oscillations between upward and downward motion) in the upper troposphere as a result of deep convection are clearly simulated by the cloud model. All of these features are associated with observed tropical squall lines.

(b) Heat and Moisture Budgets

Time series of the apparent heat source Q_1 diagnostically determined by soundings and explicitly calculated from the cloud model for the period 19-27 December 1992 are illustrated in Figs. 4 (a) and (b). The pattern of temporal variability between the heating profiles derived from the soundings and those estimated from the cloud model is quite similar. The latent heat release associated with all five major rainfall events is well simulated by the cloud model. Model results, however, show more temporal variability. Figure 4 also shows the time series of the cloud model Q_1 for the convective and stratiform regions, respectively, during the period 19-27 December 1992. The typical convective and stratiform heating structures (or shapes) are well captured by the cloud model. For example, the convective profiles show heating throughout the troposphere which is maximized in the 600-650 mb level. In the stratiform

region, heating is maximized in the upper troposphere (around 400 mb) while cooling prevails below the melting level. Another interesting feature is that the heating structure in the stratiform region is smoother than that in the convective region. This is because convective bursts have a shorter temporal evolution than that of the stratiform region where mesoscale processes are dominant. Also, Fig. 4(d) indicates that there is stronger heating aloft and stronger cooling below in the stratiform region. The cooling in the lower troposphere is from the evaporation of rain that originates from the melting of precipitating ice particles. These ice particles are generated by deposition processes aloft. These different heating and cooling patterns between the convective and stratiform regions are consistent with observed mesoscale convective systems.

Figure 5 shows the apparent moisture sink Q_2 diagnostically determined by soundings and explicitly calculated from the cloud model. As the apparent heat source, the cloud model can reproduce observed features well. Five major convective events are well simulated by the cloud model. In the convective region, it is all drying and its maximum level is lower than the apparent heat source. The drying is caused by the condensation processes associated with active cloud updrafts. Cloud model results also indicate that the condensational heating and drying mainly takes place in active cloud updrafts. In the stratiform region, there is strong moistening (by evaporative cooling) below the 600 mb level with weak drying aloft. These features in the convective and stratiform regions are typical for mesoscale convective systems from modeling and observations. The cloud model results also showed that the transport of heat by cloud drafts is one order smaller than the microphysical processes. On the other hand, the moisture transport by cloud drafts is on the same order as the microphysical processes.

4. Modeling Tropical Convective Systems - Dynamic Aspects

(a) Mass Budgets

Cloud mass flux is an important quantity for the parameterization of cloud systems in large-scale models, and is a quantity which is almost impossible to observe especially over a large area. Figure 6 shows the 7-day evolution of

cloud mass fluxes produced by the cloud model. The updraft and downdraft mass fluxes are for model grid points having total condensate larger than or equal to 0.1 g kg^{-1} . The total cloud mass flux is the sum of the updraft and downdraft mass fluxes. The larger mass fluxes are consistent with the development of organized cloud systems (non-squall clusters - days 2 and 5, and squall line - day 4). Downdraft mass fluxes have a magnitude about half that of the updraft mass fluxes. Evaporative cooling associated with the downdrafts is also about half of the condensational heating associated with the updrafts (Table 2). Cloud model results also showed that active updrafts account for approximately 75% of the cloud updraft mass flux yet only cover about 12-14% of the total area. This result is consistent with the "hot towers" concept that convective towers play a critical role in the heat and moisture budgets in the tropics, even though they only occupy a small fraction of the area. In contrast, active downdrafts only account for about 30% of cloud downdraft mass fluxes. These cloud model results suggest that most downdrafts are rather weak, and only a small area of downdrafts can be very active.

(b) Momentum Budgets

In general, the vertical convergence of horizontal momentum fluxes and the horizontal perturbation pressure gradient force are the two dominant terms in the momentum budget. The convective updrafts can bring negative momentum from the low levels upward to the middle and upper environment. Convective and mesoscale downdrafts can bring positive momentum from the middle levels downward to the near surface environment. Mixing could occur at the leading edge of the convection between the cold outflow boundary and the high θ_e air within the inflow. All these processes can reduce the vertical shear of horizontal momentum. However, the meso-high associated with the cold outflow and the meso-low located at middle levels within the squall system can generate u-momentum (relative to the environment). This pressure-gradient-force-generated momentum can also be transported upward and downward by cloud drafts.

5. Modeling Interactive Cloud-Radiation processes

(a) Diurnal Variation

Sensitivity tests using a two-dimensional cloud model have been performed to determine the "mechanisms" associated with the diurnal variation of precipitation processes over tropical oceans. The run that did not allow for the diurnal variation of radiative processes did not produce a diurnal variation of rainfall. The diurnal variation of rainfall was still simulated even when the diurnal variation of SST was not allowed. However, the maximum rainfall was shifted from 2 AM to 3-6 AM. These results suggested that the diurnal variation of sea surface temperature could modulate rainfall processes, but it may only play a secondary role in diurnal variation. The cloud model results also indicated that modulation of convection by the diurnal change in available water as a function of temperature was responsible for a maximum in rainfall after midnight. This simply implies that the increase (decrease) in surface precipitation associated with longwave cooling (solar heating) was mainly due to an increase (decrease) in relative humidity. However, the physical processes responsible for diurnal precipitation were found to be different in another cloud model study. In that cloud model study, the direct interaction of radiation with organized convection was the major process that determined the diurnal variability of rainfall. Well (less) organized cloud systems can have strong (weak) diurnal variations in rainfall. Ice processes are needed to produce the diurnal variation of precipitation. The model set-ups between these two cloud model studies are quite different, however. In one cloud model study, the horizontal momentum was relaxed to its initial value which had a strong vertical shear. Consequently, only long-lived squall lines (or fast-moving convective systems) were simulated over the entire simulation [Fig. 8(a)]. On the other hand, the horizontal wind was nudged to time-varying observed values in another. The simulated cloud systems, then, had many different sizes and various life cycles [Fig. 8(b)].

(b) Equilibrium Thermodynamic States in the Tropics

Recently, cloud resolving models were used to study the tropical water and energy cycles and their role in the climate system. The models are typically run for several weeks until modeled temperature and water vapor fields reach a quasi-equilibrium state. However, two cloud models produced different quasi-equilibrium states (warm and humid vs cold and dry) even though both used

similar initial thermodynamic profiles, horizontal wind, prescribed large-scale vertical velocity and fixed sea surface temperature (SST). Sensitivity tests were performed to identify the major physical processes that determined the equilibrium states for the different cloud model simulations. The results indicated that differences in the cloud-model-simulated quasi-equilibrium state can be attributed to how the atmospheric horizontal wind is treated throughout the integration. The model that had the stronger surface wind produced a warmer and more humid thermodynamic equilibrium state. Furthermore, the cloud model results suggested that one of the major physical processes responsible for the warmer and more humid equilibrium state was larger latent heat fluxes from the ocean (due to stronger surface winds). The moist static energy budget further indicates that the large-scale forcing in water vapor is another major physical process responsible for producing the warmer and more humid thermodynamic equilibrium state.

Cloud resolving models have also been used to examine the "climate hypothesis related to global warming". The major results to date are: (1) conversion of ice-phase water into the vapor phase associated with the dissipation of upper-level stratiform/cirrus clouds contributes to upper tropospheric moisture on the same order as moisture transport from deep convection, (2) cloud activity is much more sensitive to convergence in the large-scale atmospheric circulation over an oceanic warm pool than it is to the local SST, and (3) organization of cloud systems can largely determine the magnitude of "upper level cloudiness" and "upper level moisture profiles". All of the above conclusions do not say whether or not global warming is occurring. It does say, however, that if cloud processes are neglected or poorly formulated, the consequences could lead to substantial errors in formulating important climate hypotheses.

See also: Air-Sea Interaction (Momentum, Heat and Vapour Fluxes), Boundary Layers (Modelling and Parameterization), Cloud Micro Physics, Cloud-Radiative Interactions, Convection (Convection in the Ocean), Convection (Convective Transport), Convection (Theory), Convective Storms, Convective Storms (Convective Initiation), Convective Storms (Convective Storm Modeling), Density Currents, Diurnal Cycle, Mesoscale Meteorology (Mesoscale Convective

Systems), Mesoscale Meteorology (Models), Mesoscale Meteorology (Overview), Numerical Models (Methods), Observation Platforms (Aircraft), Observation Platforms (Balloons), Parameterization of Physical Processes (Clouds), Parameterization of Physical Processes (Convective Heating), Parameterization of Physical Processes (Overview), Radar (Doppler Radar), Radar (Precipitation Radar), Radiative Transfer (Cloud-radiative Processes), Radiosondes, Satellite Remote Sensing (Cloud Properties), Satellite Remote Sensing (Precipitation), Thermodynamics (Saturated Adiabatic Processes), Tropical Meteorology, Turbulence and Mixing, World Climate Research Program.

6. Further Reading

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Figure Captions

- Fig. 1 Representation of the three-class ice scheme used in the cloud model.
- Fig. 2 Time-sequence of the two-dimensional cloud model estimated domain mean surface rainfall rate (mm h^{-1}) for **(a)** the west Pacific warm pool region and **(b)** the east Atlantic region.
- Fig. 3 **(a)** Horizontal and **(b)** vertical cross-sections of vertical velocity (filled contours) and total cloud mixing ratio (solid contour) taken from a three-dimensional cloud model simulation of the west Pacific warm pool region precipitating system (during a Westerly Wind Burst period). The location of the vertical cross-section is depicted by the solid line in the upper figure.
- Fig. 4 Evolution of the apparent heat source (Q_1) averaged over the west Pacific warm pool region for the 8-day period 19-27 December 1992 (West Pacific warm pool region). **(a)** Derived diagnostically from soundings. **(b)** Simulated from the cloud model. The cloud model simulated Q_1 over **(c)** the convective region and **(d)** the stratiform region.
- Fig. 5 As Fig. 4 except for the apparent moisture (drying) source (Q_2).
- Fig. 6 Evolution of domain-averaged **(a)** updraft, **(b)** downdraft and **(c)** total mass flux for the east Atlantic cloud systems simulated in the cloud model.
- Fig. 7 Momentum budget.
- Fig. 8 Time sequence of the cloud model estimated domain mean surface rainfall rate (mm h^{-1}) for **(a)** a run where the horizontal momentum was relaxed to its initial value (containing strong vertical shear) and **(b)** a run where the horizontal wind was nudged to time-varying observed values.

Table Captions

- Table 1 Major highlights of cloud resolving model (CRM) development over the past four decades.
- Table 2 Cloud-model-simulated domain-average surface rainfall (mm), stratiform amount (percentage) and microphysical processes (ratios between evaporation and condensation, sublimation and deposition, and deposition and condensation) for (a) the west Pacific warm pool region and (b) the east Atlantic region. For west Pacific warm pool region, the cloud model results are also separated into sub-periods, deep strong convection during December 20-23 and 24-25 and weaker convection prior to, in between, and after the deep convection (December 19-20, 23-24, and 25-26, 1992). Slow-moving (non-squall, September 2-4), fast-moving (squall, September 4 to 6) and less organized (September 6 to 8) periods for the cloud model simulated east Atlantic region results are also shown.

	Major Highlights
1960's	Loading, Buoyancy and Entrainment
1970's	Slab- vs axis-symmetric model Cloud Seeding Super Cell Dynamics Cloud Dynamics & Warm rain
1980's	Ensemble of clouds - cumulus parameterization Cloud interactions and mergers Ice processes Squall Line Convective and stratiform Wind Shear and Cool Pool Gravity wave and Density Current Large-scale and cloud-scale interactions Cloud Radiation Interaction
1990's	2D vs 3D Land and ocean processes Multi-scale interactions Cloud Chemistry Process modeling - Climate Variation Implications GEWEX Cloud System Study (GCSS) Coupled with microwave radiative model for satellite cloud retrieval (TRMM)

Table 1

West

East Atlantic Region

September 2-8, 1974

a

	1969	1970	1971	1972
Total Sfc Rainfall (mm)	153.9	29.06	124.84	
Stratiform Amount (%)	45%	42%	55%	
Evaporation/Condensation	71%	80%	69%	
Sublimation/Deposition	50%	56%	48%	
Deposition/Condensation	39%	39%	39%	

East Atlantic Region (September 2-8, 1974)

b

	September 2-8	Slow Moving September 2-4	Fast-Moving 4-6	Random 6-8
Total Sfc Rainfall (mm)	91.46	43.34	39.62	8.50
Stratiform Amount (%)	32%	27%	26%	44%
Evaporation/Condensation	54%	58%	44%	68%
Sublimation/Deposition	32%	36%	27%	24%
Deposition/Condensation	22%	23%	25%	9.5%

Table 2

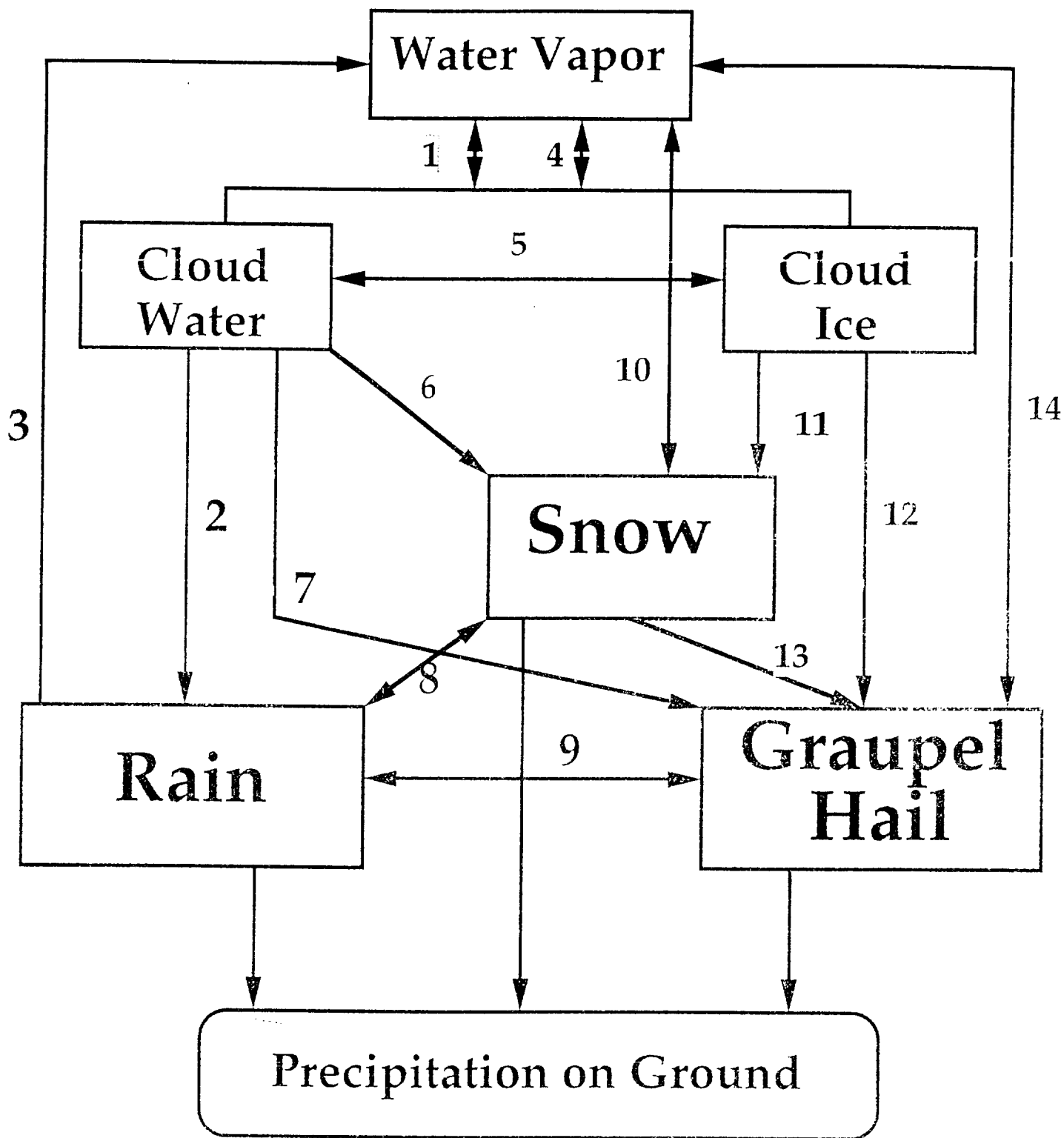


Fig. 1

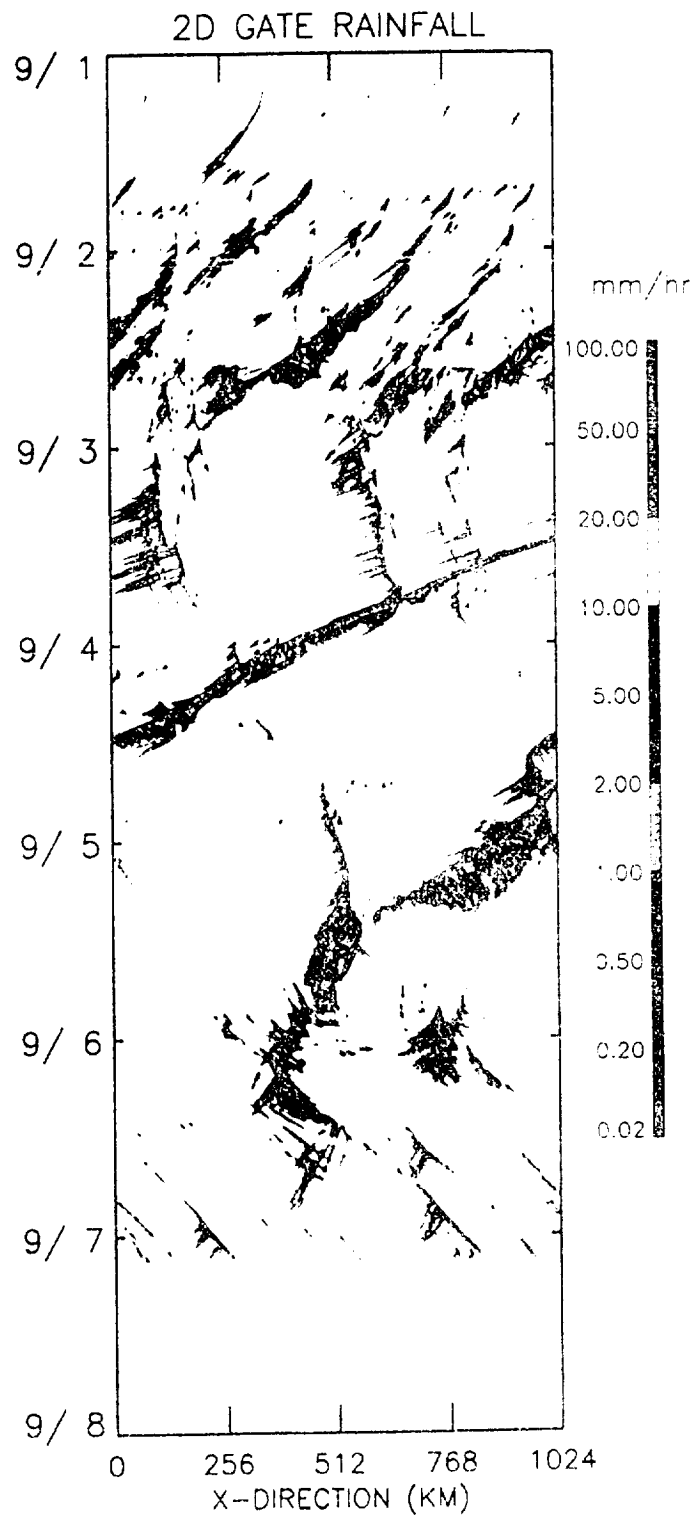
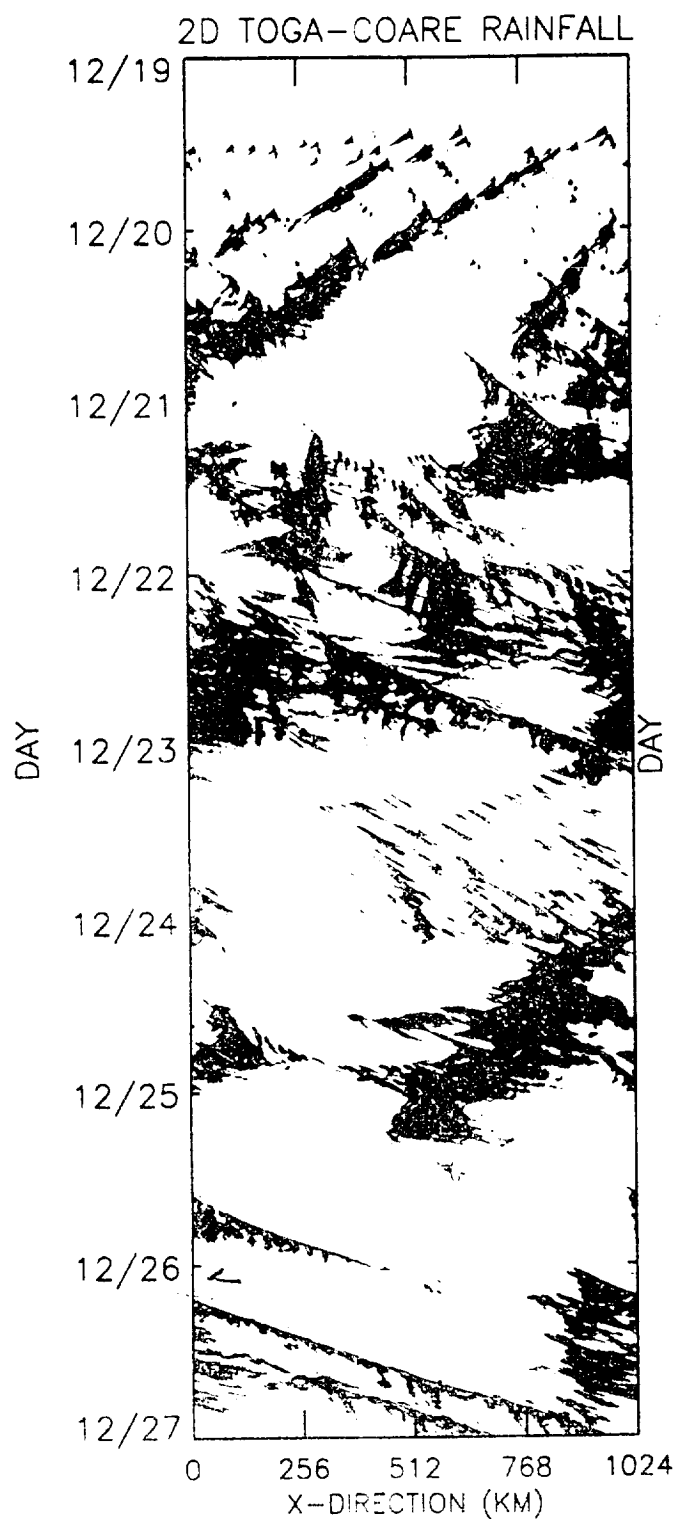
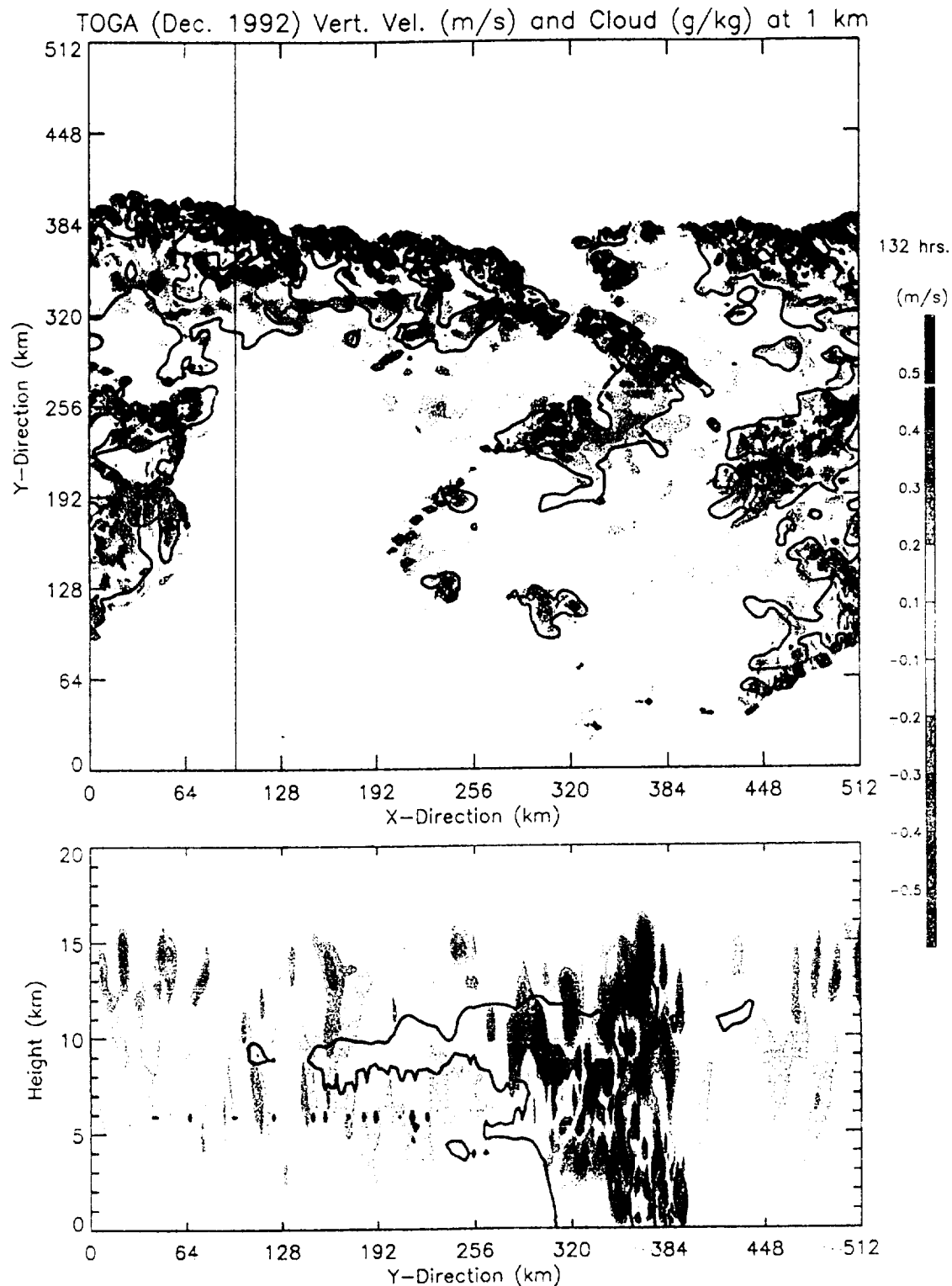


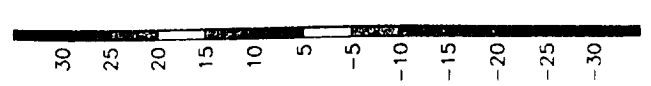
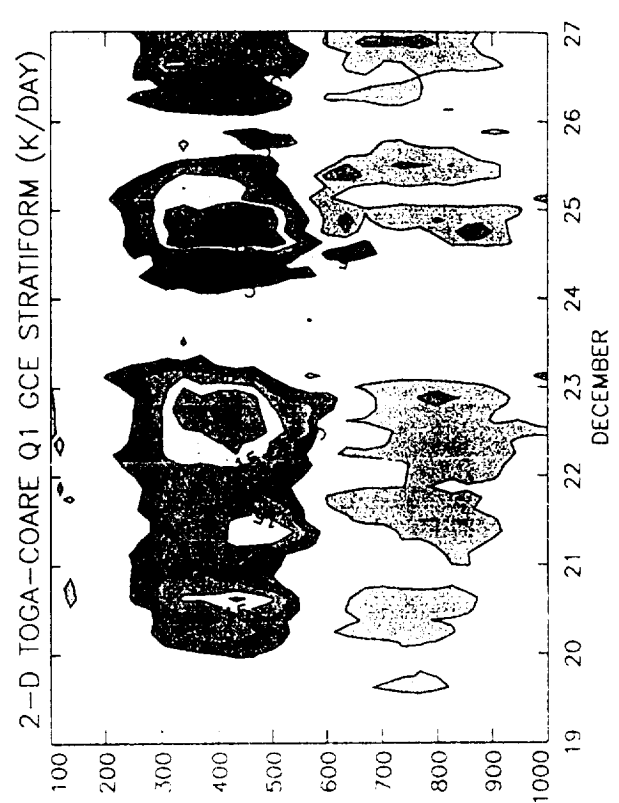
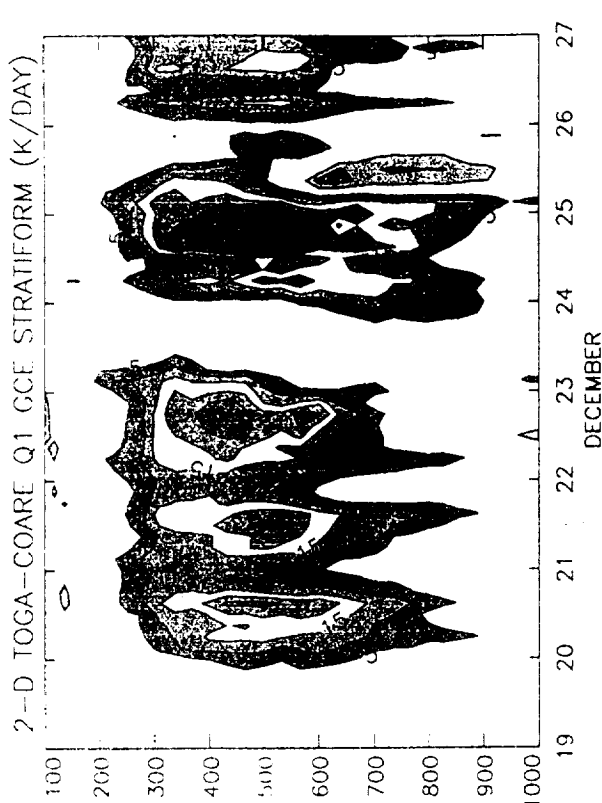
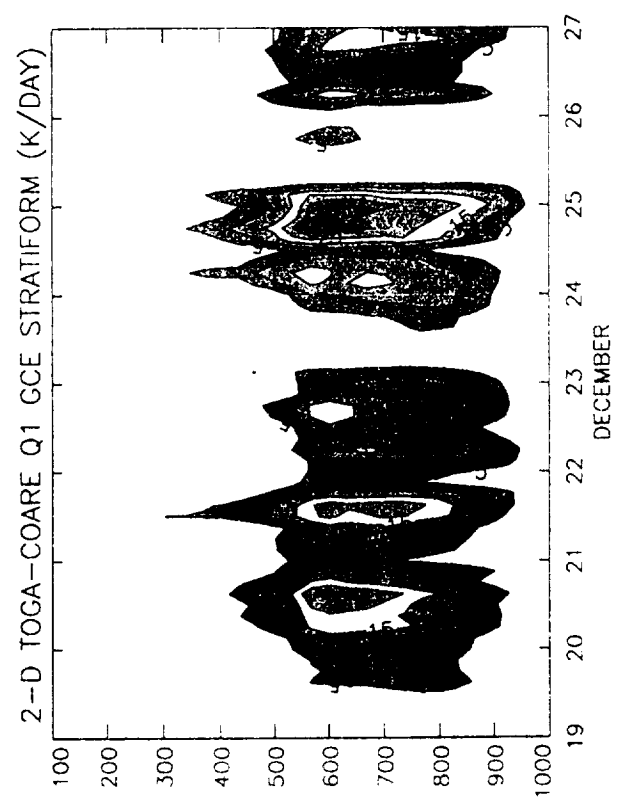
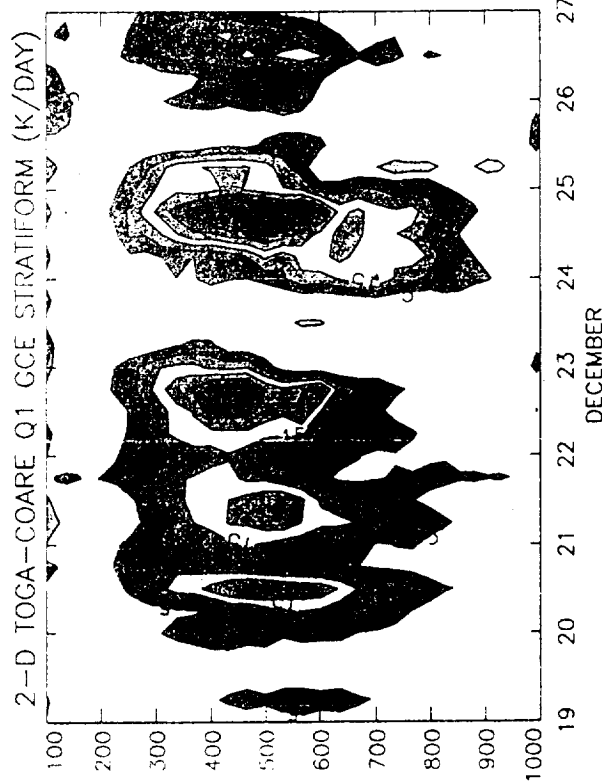
Fig. 2

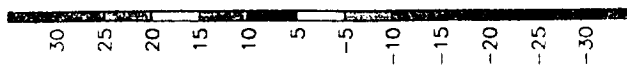
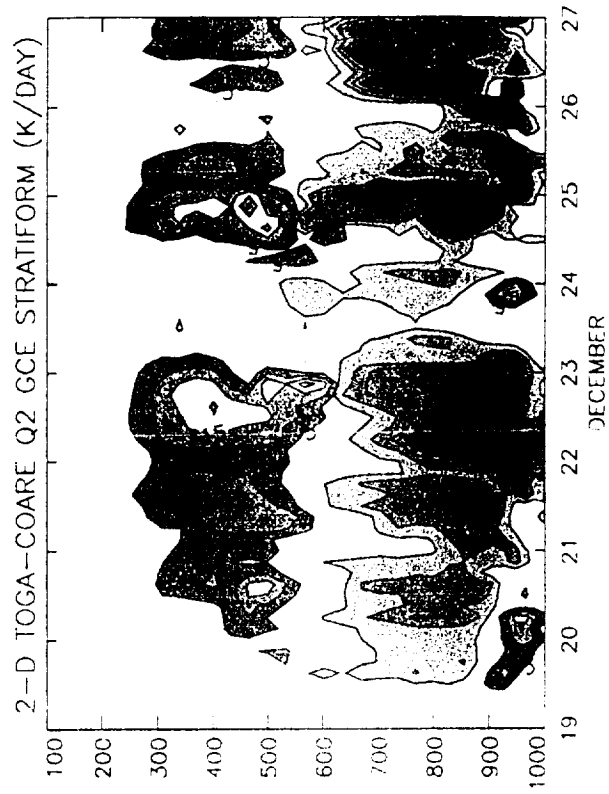
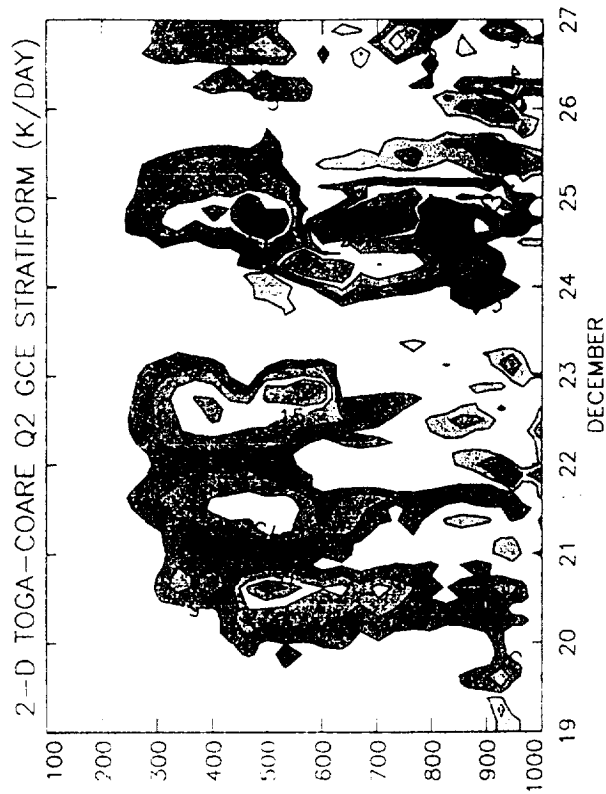
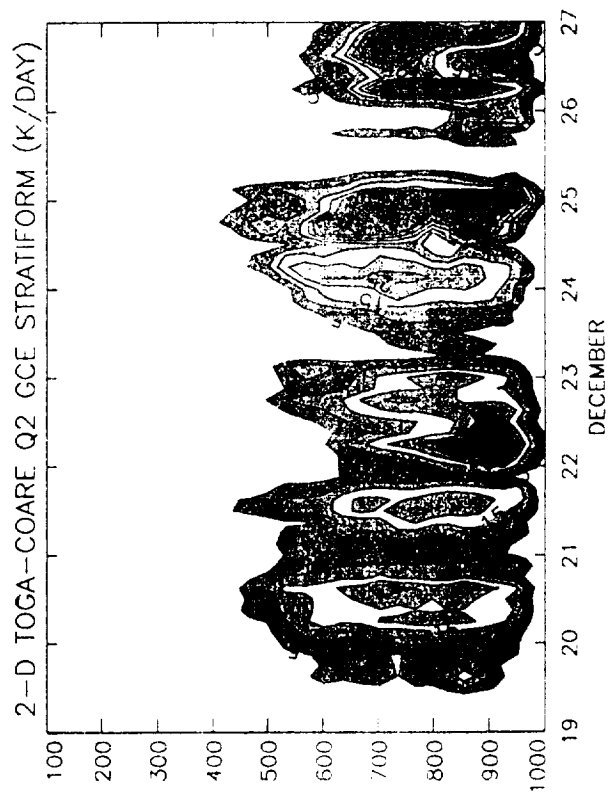
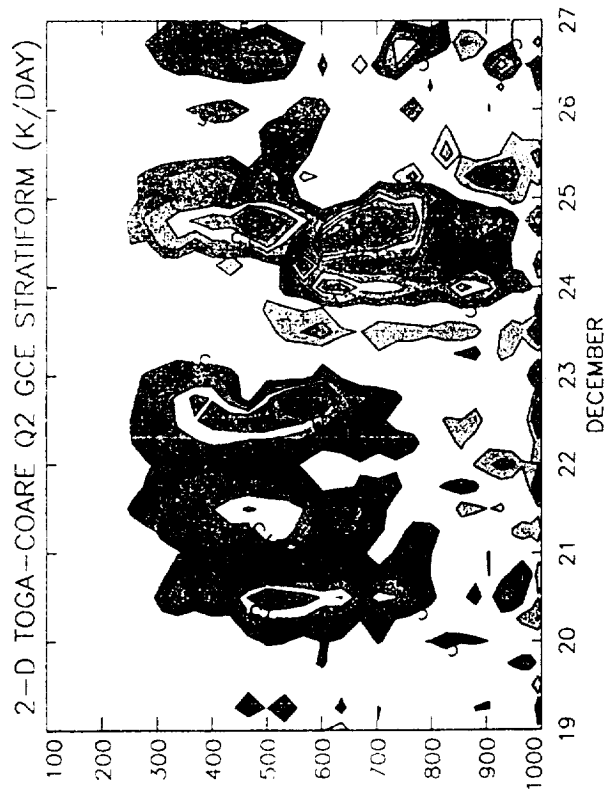


Horizontal 1-km (top), and vertical (bottom) cross-sections of vertical velocity (filled contours), and total cloud mixing ratio (solid contour) taken from a GCE model simulation of TOGA-COARE IFA convection at 132 hours (beginning at 00 UTC 19 December 1992). The location of the vertical cross-section is depicted by the solid line in the upper figure.

b

Fig. 3





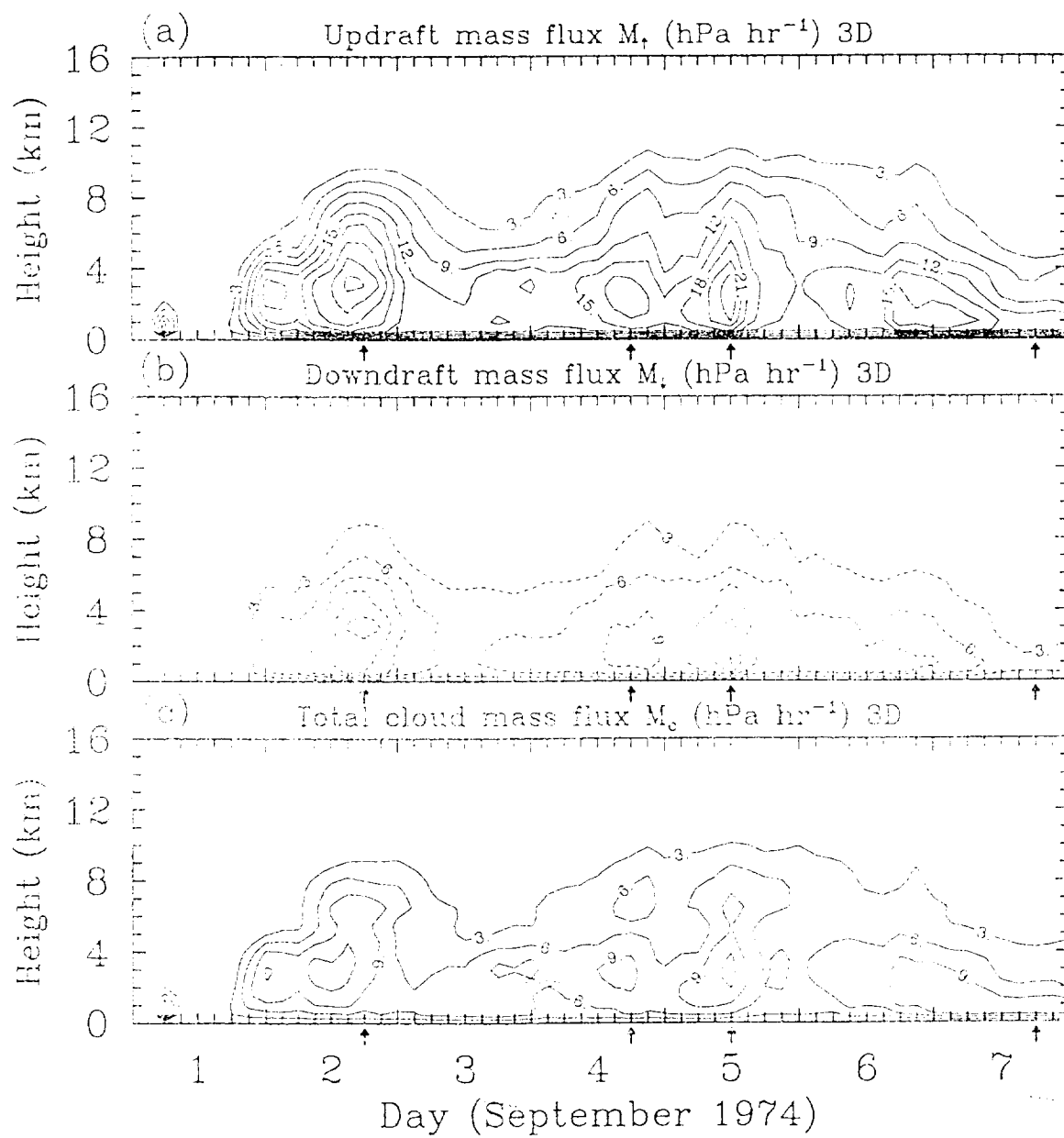
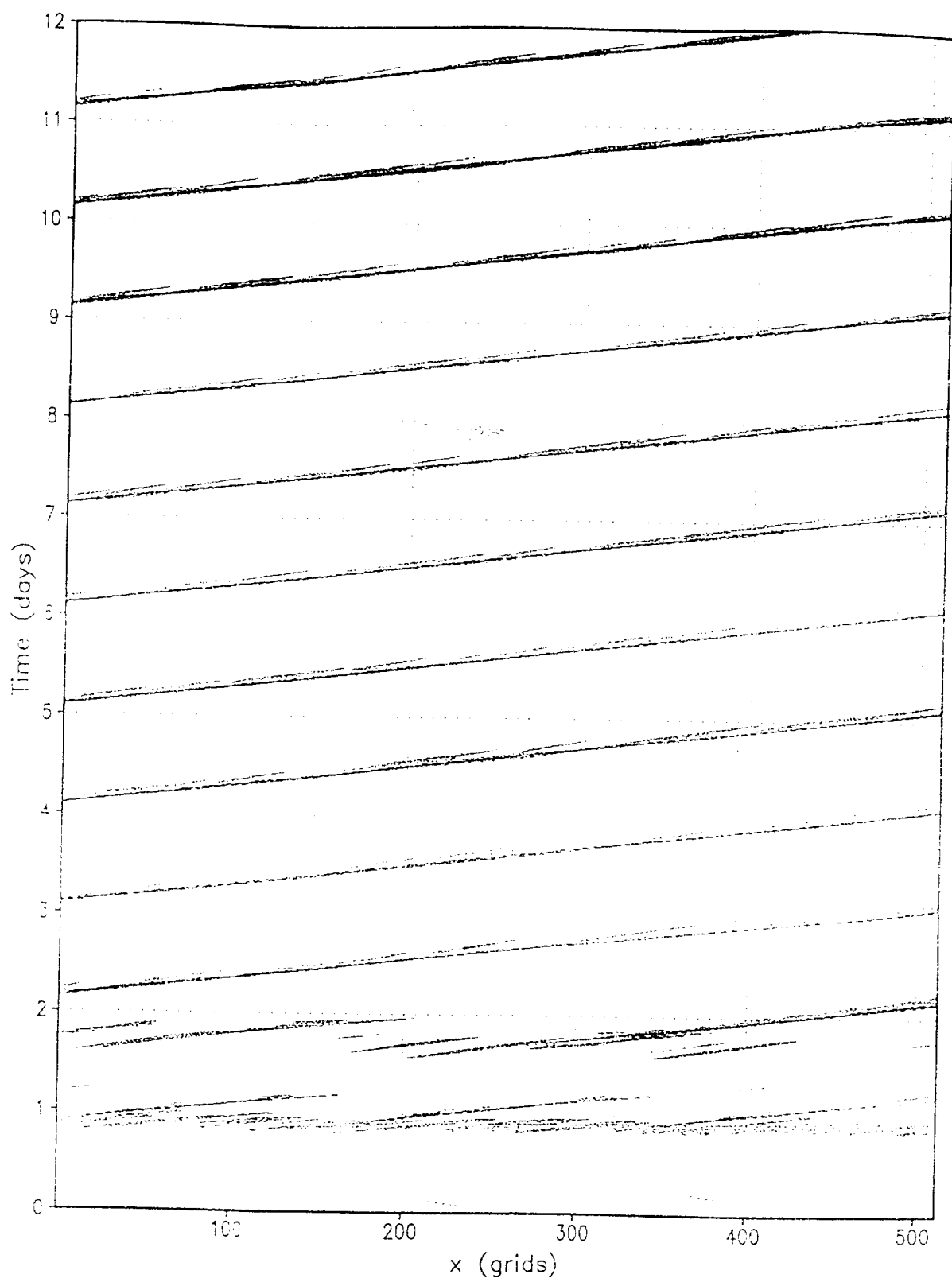
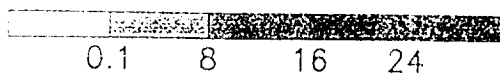
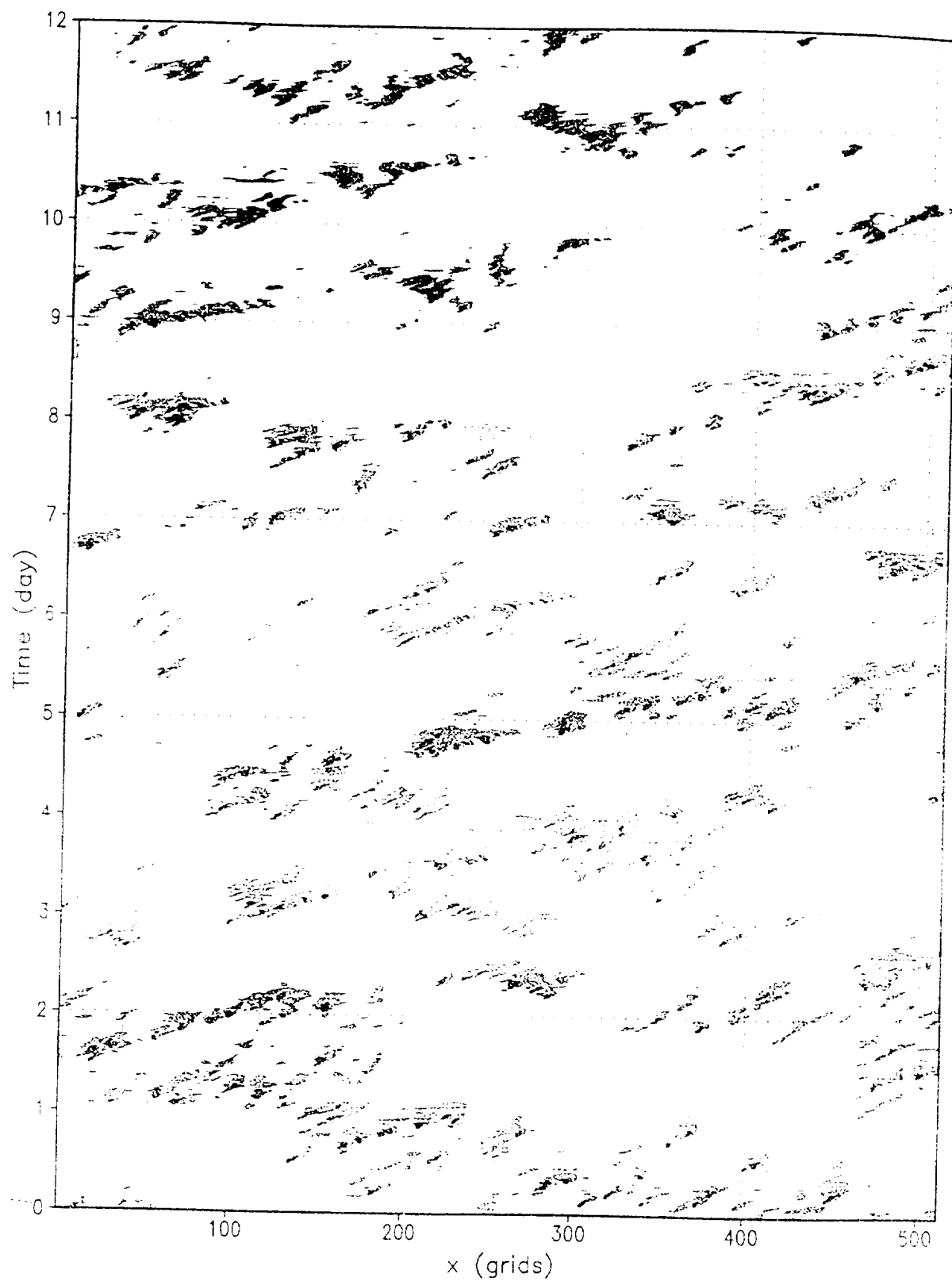


Fig. 6



Time-space distribution of rain rate (mm/hr)





Time-space distribution of rain rate (mm/hr)

